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MICRO AND NANO PLASTICS IN AGRICULTURAL SOILS

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ABSTRACT

Micro and nano plastics are global soil pollutants that poses potential threats to the ecosystem because of its extensive and possible threats to the ecological system. However, many aspects of microplastic in soil, such as its sources, distribution, and impacts, are still unclear. This is because of the challenges and limitations in measuring and studying microplastic in complex soil samples. In this review, the current knowledge on microplastic in soil was summarized, covering its fate and transport, detection, occurrence, characterization, source, and risk to soil and human. It also explores how MNPs interact with soil physical and chemical properties, their toxicity to soil biota, and the potential for MNPs to serve as vectors for pollutants and pathogens. Microplastic was found to be ubiquitous in soil matrices worldwide but here is a lack of adequate research on microplastic in soil, especially in Nigeria. Microplastic enters the soil from different sources and accumulates over time. Some studies suggest that microplastic may interact with other pollutants and affect soil quality and function, and even move along the food web. This review provides a comprehensive understanding of MNPs in agricultural soils useful to guide efforts in mitigating their adverse effects. It has been found that impacts of microplastic in soil depend on its shape, composition, and environmental factors. Several research gaps that need to be addressed were also identified.

KEYWORDS: Microplastics, Nano plastics, Agricultural Soil, Degradation.

INTRODUCTION

Plastics are widely utilized in modern agricultural farms, food production systems, and various other aspects of daily life due to their numerous advantages, such as being inexpensive, lightweight, moldable, versatile, durable, and resistant to corrosion and flames [1]. In addition to their use in households and industries, plastics are extensively employed in agriculture, where they contribute to improving crop yields, conserving water, and protecting crops from pests and diseases [2]. However, when plastics enter the soil, they can create global environmental issues. Due to their persistent nature, plastics tend to accumulate in different environmental matrices [3] and eventually break down into smaller fragments known as micro- and nanoplastics (MNPs). MNPs are small fragments of synthetic polymers that are prevalent in terrestrial environments, the atmosphere, and can accumulate in oceans, rivers, lakes, as well as in drinking water and food if not properly managed. As a result, they are identified as emerging particulate anthropogenic pollutants. Studies [4] have shown that the presence of MNPs contamination in agricultural soils is widespread, reaching up to 63 kg/ha in some regions. Another study [5] found that MNPs are persistent in the environment, with some lasting over fifty years. The presence of MNPs in agricultural soils can negatively impact soil health, crop quality, biodiversity, ecosystems, and food safety, and they can be inhaled by both humans and animals. The term "microplastics" was first introduced in a report [6] on small plastic fragments in the marine environment, an upper size limit of 5 mm for microplastics was later proposed [7].

Nanoplastics are particles and fibers smaller than 1 μm, while microplastics range from 1 μm to 1 mm in size. Fragments between 1 and 5 mm can be classified as large microplastics [8,9]. Sources contributing to the release of plastics into the environment include wastewater treatment plants, polymer coatings on fertilizers, plastic mulch films, unauthorized dumping, and waste mismanagement. The diversity and complexity of plastic sources, usage patterns, emission pathways, and material properties are reflected in the wide variety of MNP particles, which exhibit a broad range of physical, chemical, and biological characteristics, such as size, shape, density, polymer type, and surface properties. As a result, advanced methods are necessary for the reliable identification, quantification, and characterization of these particles, making them one of the most challenging analytes in environmental and food contexts. Several reviews have focused on the detection, identification, and quantification methods for MNPs. The importance of chemical analysis for reliable MNPs identification cannot be over emphasized, only FTIR spectroscopy was in use initially. Subsequent reviews have documented advances in both spectroscopic and thermoanalytical approaches. A review [10] recently provided a critical evaluation of analytical methods, emphasizing the need for harmonized and cost-effective analysis of MNPs. It also reported that in the past three years, there has been increased focus on the chemical analysis of small microplastic and nanoplastic particles. Physical factors such as weathering and mechanical breakdown are the primary causes of plastic deterioration, and MNPs can undergo physical and (bio)chemical degradation processes in the environment.

The issue of plastics entering the soil has become a global concern. The level of MNP contamination correlates with the production of thermoplastics like high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) [11]. In addition to these conventional polymers, other plastics such as polymethyl methacrylate (PMMA), polyamide (PA), and polyurethane (PUR), as well as biodegradable or bio-based plastics, are also produced. Biodegradable plastics are increasingly used in agriculture (e.g., polybutylene adipate-co-terephthalate, PBAT) and food packaging (e.g., polylactide, PLA). Synthetic polymers also serve as film formers in multicomponent systems composed of binders, pigments, fillers, and additives, such as curing coating systems (including polyester (PES), alkyds, epoxy resin, and urethane resins), and physically drying systems (like acryl and vinyl (co)polymers).

MNPs in agricultural soil represent an emerging environmental issue that requires further research and monitoring. The detection of MNPs in agricultural soils is becoming increasingly crucial for several reasons. According to Wang et al., [12], due to the persistent nature of MNPs, nearly 40% of those that reach agricultural soils cannot be recovered and instead break down into even smaller fragments.

Furthermore, MNPs can absorb persistent organic pollutants [13] and toxic metals [14] from the soil, serving as carriers for pathogenic and/or antibiotic-resistant microorganisms. Therefore, it is crucial to assess the sources, fate, and impacts of MNPs in agricultural soils to mitigate their negative effects on soil fertility, plant growth, and overall soil health.

The purpose of this review is to offer insights into existing research on the presence and sources of MNPs, their influence on soil physical and chemical properties, their toxicity to biota, and the regulations for mitigating MNPs in agricultural soils. This includes understanding how MNPs affect soil health, plant growth, and the broader ecosystem. The review takes an interdisciplinary approach, drawing on findings from environmental science, soil science, agriculture, toxicology, and public health. It also examines current policies, technological solutions, and best practices aimed at reducing MNP pollution in agricultural soils. These insights not only shed light on the issues associated with MNPs but also aid in developing effective mitigation strategies and revising or establishing new regulations for controlling MNPs in agroecosystems.

Classification of MNPs in Agriculture

MNPs can be categorized into two groups based on their origin: "Primary" MNPs include items such as pellets used in industrial production, industrial cleaners, polymer coatings for fertilizers, plastic micro and nanobeads found in personal care products or turf pitches, microfibers released from clothing and textiles like fishing nets, and plastic mulch films used in modern agriculture [15,16]. They are intentionally manufactured in specific sizes and shapes to serve various commercial purposes. Secondary MNP particles and fibers, such as nylon or Polyamide (PA) fibers and Polyester (PES), are generated through the degradation and mechanical abrasion of larger plastic debris in the soil, caused by mechanical wear and tear of plastic-containing items, UV radiation, and (micro)biological degradation [17]. They also include plastic mulching films that break down due to weathering, leaving microplastics in the soil. Improper disposal and mismanagement of plastic waste further contribute to soil pollution by secondary microplastics. NPs primarily result from the degradation of larger plastics [18] but have also been detected in facial cleansers [19]. MPs can be categorized based on their shape into microbeads, pellets, fibers, foam, and fragments.

Microbeads are small, spherical plastic particles produced through processes such as emulsion, suspension, and dispersion polymerization [20]. They originate from industrial products, fibers from washed synthetic garments, car tire debris, fragmented plastics from runoff in rural and urban areas, and nano plastics from cosmetics [21]. Often used as exfoliants in personal care and beauty products like facial scrubs, body washes, and toothpaste, microbeads are added to create a rough or abrasive texture that aids in exfoliation. They are typically made from materials like polyethylene, polypropylene, or other polymers and are classified as a type of primary microplastic [22]. When these products are rinsed off, the microbeads can enter drains and eventually make their way into waterways. Due to their small size, wastewater treatment plants cannot effectively remove them, leading to their accumulation in rivers, lakes, and oceans. Once in the environment, microbeads can be ingested by small organisms and may move up the food chain, potentially harming various species.

Microfibers, also referred to as synthetic fibers, are fine, cylindrical fibers with an average diameter of 10–20 μm and lengths that can reach a few millimeters. They are often shed from clothing and other textile materials, being finer than human hair, and are typically made from synthetic materials like polyester or nylon. These fibers are extensively used in textile production, including clothing, cleaning cloths, and fishing nets, due to their softness, durability, and moisture absorption capabilities. Foams and fragments, on the other hand, are generally of secondary origin, created by the mechanical breakdown of larger plastic products and often have irregular shapes. As a form of primary microplastic [22], microfibers can contribute to environmental issues when they are released into water during washing, adding to microplastic pollution.

Plastic pellets, also known as nurdles, are small granules used as industrial raw materials for the production of larger plastic products. These cylindrical or disk-shaped pieces of raw plastic resin are the foundational material for items such as packaging, containers, and toys [23]. As a form of primary microplastic [24], plastic pellets can pose environmental risks if unintentionally released during manufacturing or transport. Accidental spills or mishandling at production sites can lead to their dispersal into the environment, where they may absorb and accumulate harmful chemicals from their surroundings.

Plastic glitter, consists of tiny, shiny particles made from plastic materials, often used for decorative and entertainment purposes. These glitters are commonly found in consumer products such as cosmetics, nail polish, body lotions, and craft supplies to create a sparkling or shimmering effect. The plastic materials used in glitter production typically include polyethylene terephthalate (PET) or other polymers. Classified as a type of primary microplastic [24], plastic glitter has raised environmental concerns similar to those associated with microbeads. When products containing glitter are washed off, the particles can enter waterways, contributing to plastic pollution in oceans and other aquatic environments. Once in the environment, glitter particles can persist for long periods and may be ingested by marine life, posing significant ecological risks.

Plastic fragments are small pieces or particles that result from the breakdown of larger plastic items, such as bottles, bags, and containers. Classified as a type of secondary microplastic [22], these fragments are not intentionally produced but are formed through natural or human-induced processes like weathering, UV radiation, mechanical abrasion, or biodegradation. The size, shape, color, and composition of plastic fragments can vary based on the type and age of the original plastic item. These fragments contribute to plastic pollution and can absorb and accumulate harmful chemicals from their surroundings, posing potential health risks.

Sources of MNPs in Agricultural soils

MNPs can come from different sources in agricultural soils such as the use of biosolids (processed sewage sludge) and compost [25]. Studies have highlighted that treated sewage sludge and compost often contain microplastics. For instance, research [26] has discussed biosolids as a source of microplastics and other pollutants. It has been noted that the transfer of MNPs from urban wastewater to agricultural ecosystems via biosolids has not been adequately addressed by regulators and scientists. Wastewater treatment facilities are considered major pathways for MNPs to enter soil systems [27], as these particles remain in the sludge after wastewater treatment. When this sludge is used as fertilizer, it can contaminate agricultural soils. This practice is also common in the European Union, where 4–5 million tonnes of sludge solids are applied to farmlands as fertilizer [28]. Studies [29,30] have indicated that sewage sludge, which contains significant amounts of microplastics, is frequently used as fertilizer in agriculture.

Plastic contaminants can infiltrate agricultural soil through various means, including damaged, degraded, or discarded agricultural plastic products, leakage from non-agricultural sources like contaminated water, air, and improperly managed waste [28]. Additionally, soils can receive plastic inputs from littering near roads and trails or illegal dumping of waste. Although the exact amount of plastic entering the soil through these methods is not well-documented, it is a common occurrence. Studies [31,32] revealed that a significant portion of trash washed from highways during storms contained non-degradable items like plastic, with trash loads ranging from 0.85 to 6.6 kg per hectare.

Furthermore, particles from tire abrasion on roads can enter the roadside environment through dust or wash-off, becoming pollutants [33,34]. Larger plastic items can also be washed or blown away, contaminating nearby fields.

Practices such as using greenhouses, organic fertilizers [35], water pipes, plastic greenhouse covers, polymer-based fertilizers, pesticides, seed coatings, and plastic mulch films [36] can introduce MNPs into soils. Plastic mulching, which involves placing plastic sheets on the soil surface to conserve moisture, regulate temperature, and prevent weed growth, is a common method to enhance crop yields and water efficiency. This technique, while beneficial for crop production, also introduces plastics into the soil, leading to environmental harm due to the release of harmful additives. High-density, low-density, and linear low-density polyethylene (PE) are commonly used for mulching, while polyvinyl chloride (PVC) mulches are banned in many countries due to their toxicity and cancer risks. The use of thin plastic films results in higher residual levels of plastic mulch, disrupting moisture and nutrient transport, hindering root growth, decreasing seed germination, inducing salinization, and accumulating harmful chemicals like phthalate esters, aldehydes, and ketones in soils [37]. Studies have shown that plastic mulches contain significant amounts of phthalates, with levels in mulched soils being 74 to 208% higher than in non-mulched soils in China. Research has also found that plastic pieces in soil increase with plastic mulching, releasing pollutants like phthalates and contributing to environmental contamination. For example, PE film pieces from plastic mulching were found to constitute 10% of the total soil surface sampled in crop fields.

Aerial deposition and transport from landfills are also sources of MNPs in agricultural soils [38]. MNPs can be blown from poorly managed landfills or streets and carried by wind [39] over long distances, eventually settling in soils [40]. Although there are limited studies on air deposition of MNPs, it is suggested that this could be a significant source of microplastics in urban and suburban soils. Research [39] has shown that air can transport MNPs to soils, and particles from landfills can contribute to soil contamination. Additionally, runoff and deposition from roads or cities can pollute nearby soils. Agricultural soils affected by floods tend to have higher levels of MNPs [41].

Degradation refers to the breakdown of larger plastic items in landfills and the environment. This process produces both microplastics [42] and nano plastics [43]. The degradation of plastic waste is a primary source of MNPs in the environment [43]. The sources of MNPs in soil include agricultural practices, runoff and deposition, and the breakdown of larger plastic pieces. Additionally, health and beauty products, particularly body and face scrubs, are significant sources of nano plastics [19].

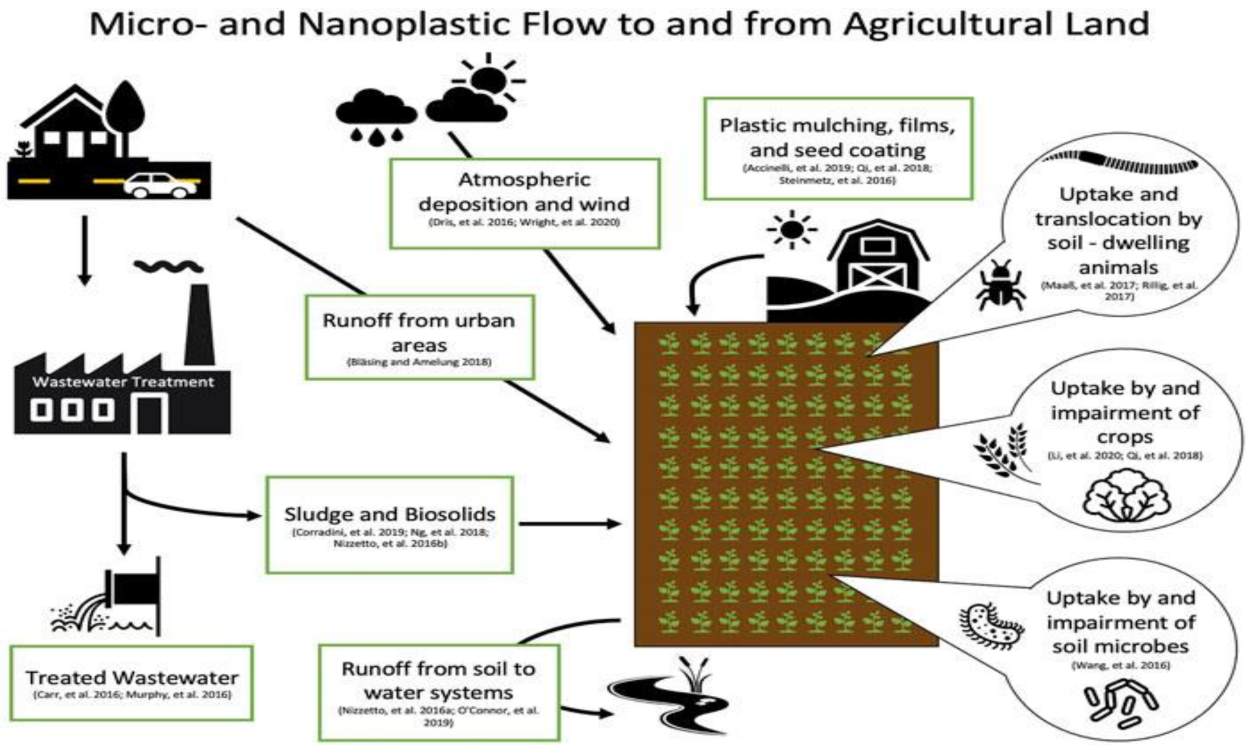

Fig 1. Micro and nanoplastic flow to and from the environment. Source; Frontiersin.org [44]

Properties, Characteristics and Types Of Plastics Commonly Found in Agricultural Settings

The plastics commonly found in agricultural settings are, LDPE (low density polyethylene), HDPE (high density polyethylene), PVC (polyvinylchloride), PET (polyethylenterephthalate), PS (polystyrene), and PP (polypropylene) of mesoplastics, MP and NP, polyacrylic acid, polyamide, polyethersulfone (PES), polyurethane (PU), and polyacrylonitrile [45].

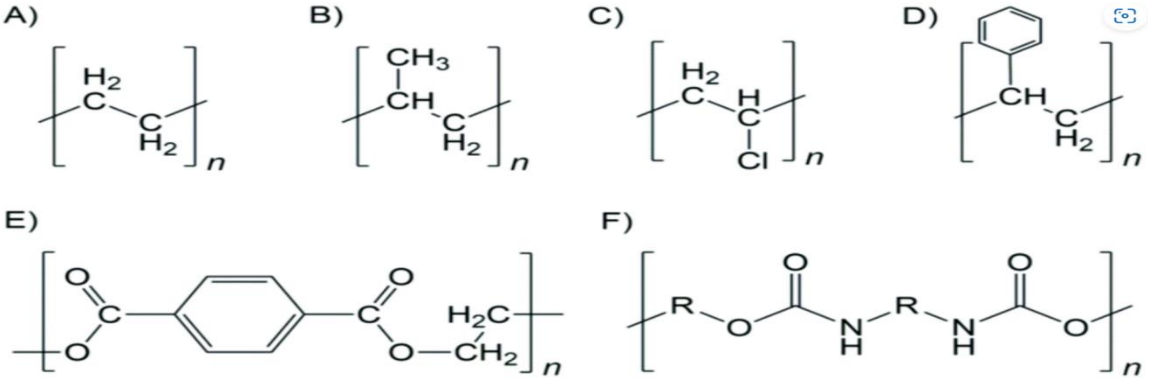

Fig. 2. Chemical structures of polyethylene (A), polypropylene (B), polyvinyl chloride (C), polystyrene (D), polyethylene terephthalate (E) and polyurethane (F).

The properties and complexity of MNPs can be characterized by:

- ***Broad size range***: From 1 µm to 1 mm for nanoplastics and up to 5 mm for larger microplastics.
- ***Variety of polymer types***: Including conventional and biopolymers with different structures and densities.
- ***Diverse shapes***: Such as fragments, spheres, irregular particles, fibers, films, and foams.
- ***Various additives***: Including antioxidants, light stabilizers, plasticizers, flame retardants, pigments, and more. They also include weathering products and absorbed contaminants like persistent organic pollutants, antibiotics, and heavy metals.

Fate And Transport In Soil Environment

The fate and transport of MNPs in soil was reviewed [46], highlighting that MNPs are influenced by both abiotic factors (such as soil pores, leaching, runoff, and wind) and biotic (including soil fauna, microorganisms, and plant roots) factors [47]. The migration process [48] of MNPs can also be affected by the physical and chemical properties (sizes, types, shapes, and surface properties).

Particles with a diameter of 1 µm are mobile, but the soil must have larger pores to transport MNPs effectively. Smaller nanoplastic particles tend to diffuse only to the soil surface [49]. Polycyclic aromatic hydrocarbons [50], heavy metals, engineered nanomaterials, and organic contaminants can accumulate on MNP surfaces [51], leading to their co-transfer to the soil. Once these contaminants are bound to MNPs, separating them becomes challenging.

Persistence And Degradation Processes

When MNPs accumulate in the environment, they are subjected to abiotic factors such as light, temperature, humidity, and mechanical effects, as well as biotic weathering and degradation processes, breaking down into smaller particles [52,53]. Plastics, once produced, used, and discarded, are not easily degradable and can persist in the environment for extended periods. The degradation process of MNPs depends on their type, location in the soil, climate, land use, and other factors.

Microorganisms also play a crucial role in the degradation of MNPs. Soil organisms contribute to the formation and breakdown of microplastics, influencing their movement in the soil and potentially transferring accumulated microplastics up the food chain [54]. Various bacterial and fungal species have been identified as capable of degrading MNPs in the soil [55,56]. For instance, the bacterium *Exiguobacterium* sp., isolated from plastic-contaminated soil, can cause a weight loss of polyethylene (PE) by about 5.7% after three months of incubation [57]. A study [58] investigated the biodegradation mechanisms of MNPs in soil, revealing that they degrade through a series of enzymatic reactions, including biodeterioration, assimilation, and fragmentation. The degradation of MNPs in soil is slow, often taking several years, with only those on the soil surface breaking down into smaller particles that can move through the soil or be taken up by plants [59,60]. Biodegradable polymers present potential solutions for reducing the environmental impact of plastics used for short-term purposes, such as cutlery. These polymers can break down through composting or exposure to UV radiation, especially in aquatic ecosystems. However, there are uncertainties regarding biodegradable polymers, including the need for specific collection and composting facilities and the low production volumes that may not justify the waste management efforts [61]. Additionally, some degradable plastics produce non-degradable byproducts. The possibility of significant and consistent biodegradation of conventional plastics in the environment remains uncertain [62].

Interaction With Soil Components, Impact On Soil Properties And Processes

Microorganisms and soil invertebrates play a crucial role in the transformation and degradation of MNPs within soil ecosystems. A critical review [63] on the interaction between MNPs and soil fauna highlighted that MNPs, when adhered to or ingested by soil fauna, can cause various adverse effects, including impacts on growth, behavior, and physiological responses such as oxidative stress, gene expression changes, and alterations in gut microbiota [64]. For instance, exposure to different sizes of polystyrene (PS) MNPs (100 nm, 1 mm, 10 mm, and 100 mm, at 10 mg/kg) resulted in more severe DNA damage in earthworm coelomocytes from micron-sized MPs compared to nano plastics [65].

MNPs pollution in agricultural soil is widespread, reaching up to 63 kg/ha in some regions [66]. These pollutants pose significant risks to soil health by altering microbial activity, soil structure, contaminant transport, and sorption behavior [67]. They impact the soil's physical and chemical properties, including water retention capacity, pore size, availability, hydraulic properties, and conductivity [68]. Microorganisms and farming practices help redistribute MNPs through the soil, affecting nutrient availability and plant productivity [60]. Microfibers, for example, reduce water-stable aggregates that contribute to soil aggregation [69]. Heavy metals and organic pollutants can adsorb onto MNPs, releasing toxic contaminants to plants and soil organisms [70].

MNPs can also alter soil bacterial community structures and interfere with microbial lipid metabolism [71]. They affect microbial processes like organic matter decomposition and greenhouse gas emissions by shifting microbial community compositions. These pollutants can negatively impact the lifespan, reproduction, and overall survival of soil microbes through bioaccumulation, metabolic disruptions, reproductive effects, and oxidative stress [63]. They impair plant seed germination, reduce root elongation, and affect plant biomass and reproductive capacity, posing risks to ecosystem functioning and soil biodiversity [69]. They can leach harmful chemicals, impacting ecosystems and potentially entering the food chain. Long-term consequences include environmental disruption and potential health concerns for organisms, including humans. MNPs can lead to soil degradation by affecting its physical structure, reducing water retention, and impeding nutrient cycling. This contamination may disrupt soil microorganisms essential for nutrient availability and accumulate toxic substances, posing risks to plant and microbial health. Overall, these factors contribute to soil fertility decline and potential ecological consequences.

Effects On Microbial Communities And Functions

MNPs can significantly impact the biological properties of soil, particularly the microbial community. Due to their lower density compared to many natural minerals, MNPs can alter soil structure and function. At an environmentally relevant concentration of 2%, MNPs can change the structure and function of loamy sand soil within five weeks [72], reducing soil bulk density. In clay soils, MNPs decrease water retention capacity more than in loamy and sandy soils [73]. Smaller-sized microplastics notably reduce soil porosity and aeration [74]. There is an inverse relationship between the number of microplastics and the number of micropores in soil. The mixing of microplastics with soil reduces pore-size distribution [75], subsequently lowering the hydraulic conductivity of saturated soils. Microplastics can also affect the distribution of soil water-stable aggregates and impair water infiltration by decreasing soil stability [69]. This impaired soil permeability and stability negatively affect the vertical growth of plant roots and, consequently, plant yield. Studies have also examined the distribution of MNPs and their impact on microbial community characteristics [76].

MNPs in plants

MNPs can be taken up and transported by plants through cracks or openings. They can accumulate in various plant organs, including leaves, stems, flowers, and fruits [77,78]. When MNPs are absorbed by plant roots and translocated, they can cause phytotoxicities, raising concerns about food safety. The mechanical strength of plant cell walls is higher than that of MNP beads, allowing MNPs to be compressed and deformed during internalization [79,80]. Studies have shown that in several food crops, such as wheat, carrot, cucumber, rice, maize, and lettuce, MNPs are taken up by roots and translocated to edible tissues [81]. A research [82] demonstrated that after polystyrene (PS) nano plastics were absorbed by cucumbers, larger particles (500 nm and 700 nm) maintained their original morphology, while smaller particles (100 nm and 300 nm) underwent significant changes during transport from the roots to the aboveground parts, with their edge structures becoming unclear.

Plant roots are a crucial pathway for the uptake of MNPs by plants and play a significant role in mitigating the adverse effects of MNP pollution. In response to exposure to MNPs, plant roots may increase mucus production [83]. This mucus, along with the hydrophobic interaction between MNPs and the cell wall, causes most MNPs to be adsorbed onto the root surface [84].

Once MNPs enter plant roots, they can be transported to the stem through the flow of water and nutrients. Recent experiments have shown that high concentrations of MNPs significantly reduce stem length and above-ground biomass in plants [85,86]. MNPs can block or reduce nutrient uptake, disrupt water movement within the plant, and cause physical damage to plant tissues.

Studies have examined the interaction between MNPs and microorganisms, toxicological assessments for animals and plants, and ecological effects [72,87,88]. Research has also focused on the effects of microplastics on plant growth and soil health [89], the ecotoxicity of microplastics [90], and their toxicity to plant root cells. The migration characteristics of microplastics and their effects on plant functionalities have been studied, revealing several adverse impacts.

For instance, MNPs can reduce root length, fresh weight, and chlorophyll content, decrease the shoot/root ratio, induce genetic changes, reduce seed setting and root/shoot ratio, alter metabolic pathways, decrease seed germination rate, dry biomass, and plant height, reduce photosynthetic metabolism in leaves, and interfere with mineral nutrition metabolism in roots, stems, and leaves. Additionally, MNPs can indirectly negatively affect plant growth and performance by altering soil physical and chemical properties, soil microbiome, and invertebrates [63].

Effects On Human Health

MNPs can enter the human body through inhalation, ingestion, and skin contact. Airborne microplastics can come from urban dust, synthetic textiles, rubber tires, aerosols from ocean waves, or airborne particles from dry wastewater treatments [91]. MNPs can also be ingested through the food chain and water sources [92], and can enter the body through wounds, sweat glands, or hair follicles.

Studies have found MNPs in honey, beer, salt, sugar, fish, shrimp, and bivalves [93]. These particles can carry harmful chemicals or pathogens that may affect the immune system, metabolism, and reproduction [94]. MNPs could harm human cells, disrupt hormone function, and act as endocrine disruptors [95]. Harmful plastic additives used in food packaging, such as phthalates, bisphenol A, brominated flame retardants, triclosan, and organotins, pose health risks.

Studies have detected phthalates in the urine of pregnant women [96], microplastics in the feces of healthy volunteers [97] and infants [98], and polyethylene microparticles in the blood of healthy adults [95]. Dermal contact, inhalation, and ingestion are major routes of human exposure to MNPs [99]. Dermal contact includes exposure to contaminated air, textiles, personal care products, and cosmetics, though this route is less prevalent due to limited skin pore size [100].

Ingestion of MNP-contaminated food, such as salt, beer, drinking water, teabags, and seafood, leads to their entry into the human body [101,102]. Food chain transfer is particularly concerning. The transfer of MNPs in terrestrial systems was reported [88], showing significant concentration ratios from soil to earthworm casts, chicken feces, and chicken gizzards, indicating potential human ingestion through food. Inhalation of MNPs occurs from both outdoor and indoor air. Direct evidence has shown MNPs in human stools, placentas, and blood circulation systems [103].

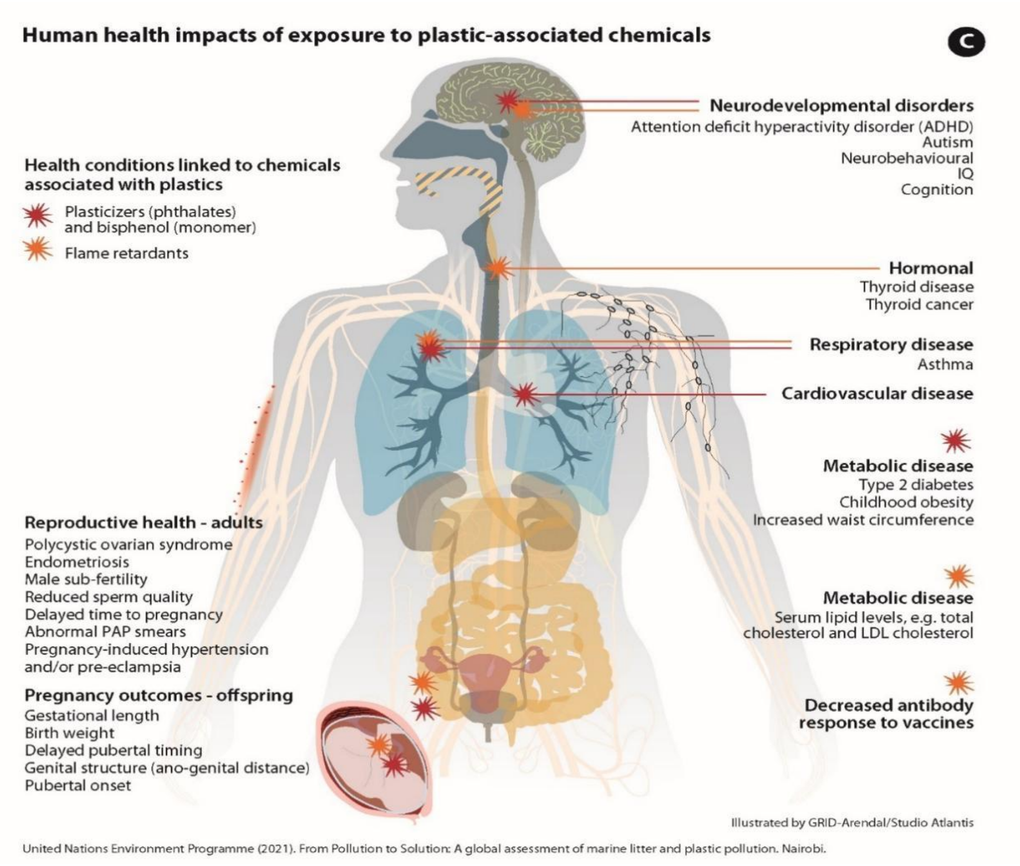

Fig. 3. Human health impacts of exposure to plastic-associated chemicals [104]

Analytical Techniques For Detection And Characterization Of Mnps

Recent reviews have focused on the extraction and identification methods of MNPs in soils [105]. Characterizing MNPs in agricultural soil involves determining, measuring, and studying the presence and effects of these small plastic particles in the soil environment. Researchers use various methods for this purpose, including sampling, extraction, separation, identification, and quantification. The identification of plastics typically involves comparing spectra with standard compounds and polymers, often with the support of libraries. For instance, the National Institute of Science and Technology (NIST05 and NIST05s) library can be used for GC-MS analysis [45]. Free libraries like SpectraBaseTM or Nicodom FTIR Spectra Libraries are useful for identifying plastics analyzed by IR and Raman spectroscopy. Additionally, literature provides lists of representative absorption bands for identifying plastics by FT-IR [106].

Several analytical methods have been used or suggested for detecting MNPs in soil, including: Fourier transform infrared spectroscopy (FTIR) is a method used for identifying microplastics (MPs) on a particle-by-particle basis. FTIR can be applied in reflection and transmission modes, or as attenuated total reflection FTIR (ATR-FTIR). It determines the polymer type of MNPs based on their infrared absorption spectra and provides information on their surface functionalization and degradation. However, FTIR has limitations in detecting small or embedded MNPs, resolving overlapping spectra, and measuring MNPs (107,108). Spectroscopic techniques like FTIR are non-destructive but are generally suitable only for identifying MPs larger than 100 µm, resulting in a loss of information on smaller particles. These techniques require extensive sample preparation, such as density separation and matrix digestion, because the IR beam cannot reach MPs covered by natural organic and inorganic matter. FTIR analysis can be used to study the distribution behavior of MPs.

Raman spectroscopy is a technique used to identify the polymer type of MNPs based on their Raman scattering spectra. It also provides information on the molecular structure and orientation of MNPs. However, this method faces challenges in detecting small or dark MNPs, avoiding fluorescence interference, and accurately measuring MNPs [107,108, 66].

Thermal analysis is a technique used to measure the thermal properties of MNPs, including melting point, glass transition temperature, and decomposition temperature. It also provides insights into the thermal stability and degradation of MNPs. However, this method faces challenges in separating MNPs from the soil matrix, identifying the polymer type, and accurately measuring MNPs [107,108].

Pyrolysis gas chromatography-mass spectrometry (Py-GC-MS) is a spectrometric method that breaks down MNPs into smaller fragments through heating, followed by analysis using gas chromatography and mass spectrometry. This technique provides information on the polymer type, composition, and additives of MNPs. However, it faces challenges in separating MNPs from the soil matrix, detecting small or degraded MNPs, and measuring MNPs [107,108]. Therefore, further research and development of improved analytical methods for detecting MNPs in soils and plants are needed. Pyrolysis GC/MS has been successfully applied for analyzing seawater microplastics and nanoplastics [109,110]. If the goal is to determine the shape and size of microplastics, spectroscopic techniques are preferred, as Py-GC-MS cannot quantify the number of micro- and nanoplastics.

Scanning Electron Microscopes (SEMs) are used to analyze MNPs in soil by creating high-resolution images of soil samples. SEMs can reveal the minute structure of MNPs, including their shape, size, and surface characteristics. This helps in identifying and characterizing MNPs within the soil matrix. SEMs can offer insights into the chemical composition of particles using energy dispersive x-ray spectroscopy (EDS), a technique commonly incorporated into SEMs. SEMs work by scanning the surface of a sample with a focused beam of electrons. These electrons interact with the atoms in the sample, producing signals that can be detected and translated into detailed images. SEMs provide detailed images of MNPs, revealing their shape, size, and surface characteristics. This high level of detail helps in identifying and characterizing MNPs within the complex soil matrix. SEMs can show the surface texture and morphology of MNPs, which is crucial for understanding how these particles interact with soil components and other environmental factors. SEMs have limitations, such as the need for extensive sample preparation and the potential for sample damage due to the high-energy electron beam. Additionally, SEMs are less effective at detecting very small or deeply embedded MNPs.

Transmission Electron Microscopy (TEM) is a powerful technique used to analyze MNPs in soil. TEM works by transmitting a beam of electrons through a thin sample, producing high-resolution images that reveal the internal structure of MNPs at the nanometer scale. TEM provides High-Resolution of MNPs, allowing researchers to observe their internal structure, morphology, and size at a very high resolution. This is useful for identifying and characterizing MNPs within the soil matrix. TEM can be coupled with techniques like Energy Dispersive X-ray Spectroscopy (EDS) to perform elemental analysis to determine the chemical composition of MNPs and any associated contaminants. TEM requires extensive sample preparation and is limited to analyzing very thin samples. It is also a time-consuming and expensive technique, which may limit its widespread use.

Current Mitigation Strategies Practices

Phytoremediation involves using plants to absorb, break down, or contain MNPs in the soil [111]. Certain plants produce enzymes or exudates that can degrade plastic polymers or promote the growth of microorganisms capable of breaking down MNPs. However, this method carries risks, such as the potential transfer of MNPs into the food chain or the release of toxic substances from plastic degradation [112].

Microbial remediation uses microorganisms like bacteria, fungi, or algae to degrade or transform MNPs in the soil [113]. Some microorganisms produce enzymes or metabolites that can break plastic bonds or make the plastic surface more susceptible to further degradation. However, this method faces challenges, including slow degradation rates, low efficiency, and potential toxicity from plastic additives or by-products [114]. While some conventional plastics can biodegrade under laboratory conditions with specific plastic-degrading organisms like *Zalerion maritimum* [115], their effectiveness in soil environments is uncertain. Laboratory studies have shown that certain strains of bacteria and fungi can degrade various polymers through enzymatic hydrolysis or oxidation [116, 62].

Emerging techniques utilize new technologies, such as enzymatic, advanced molecular, or biomembrane methods, to enhance the bioremediation of MNPs in soil [117]. Examples include using free or immobilized enzymes to accelerate plastic degradation, employing genetic engineering or synthetic biology to modify microorganisms or plants for improved plastic breakdown, and using membrane filtration or separation to remove or collect MNPs from soil [118]. However, these techniques may face limitations such as high costs, complexity, and environmental compatibility [119].

Other mitigation and remediation strategies,

The following are important for finding new solutions to deal with this environmental problem; Physical removal methods such as filtration and sedimentation can be used to reduce MNPs contamination and also raising awareness to avoid more pollution. The Prohibition of products containing MNPs in the markets and encouragement of the use of products that do not release MNPs should be employed. Regular monitoring and research to implement mandatory reporting requirements on the identification, description of use, tonnage, and the release of MNPs [120]. Putting vegetation cover on the soil can help make it stable and lower erosion, thereby stopping the movement of MNPs. Polymers that are more biodegradable or less toxic should replace conventional persistent polymers [121,122]. Restrict the use of MNPs in natural/biodegradable polymers. Advanced technologies such as electrochemical and advanced oxidation processes can also be used in breaking down plastics at the molecular level. Working together among stakeholders, including governments, industries, and communities, is needed for good waste management and recycling programs. Making strict rules on plastic use and disposal can also help reduce the impact of MNPs on soil ecosystems.

Regulatory Laws

MNPs can be regulated under the regulatory laws of Registration, Evaluation, Authorization and Restriction of Chemicals (REACH). The USA passed a regulation under the Microbead Free Water Act (MFWA) of 2015 prohibiting the manufacturing, packaging and distribution of cosmetics containing microbeads because they are microplastics for cosmetics and non-prescribed drugs. Under the regulation of the "Canadian environment Protection Act's schedule 1", plastics have been added to the list of toxic substances. With this act, the Canadian government released draft regulations in 2021 to ban single use plastics such as plastic/grocery bags, disposable plates and cutleries, straws, food packaging materials etc. The United Nations' Food and Agriculture Organization (FAO) has advocated for the 6R model (Refuse, Redesign, Reduce, Reuse, Recycle, and Recover) to minimize plastic use in agriculture [123]. Hofmann [122] recommend the "3R" waste hierarchy concept, which emphasizes reducing, reusing, and recycling plastics before disposal. Currently, there is more emphasis on addressing MNP pollution in aquatic environments than in agricultural soils, and regulations to control MNPs in soils are scarce. There are no specific restrictions for MNPs in the agricultural sector. This highlights the need for further research to better understand MNPs and their behavior in soil environments, particularly within agricultural ecosystems.

CONCLUSION

Micro and nano plastics (MNPs) are emerging pollutants that negatively impact soil health and agricultural production by altering soil properties and affecting soil organisms and their functions. They persist in soils for extended periods but can fragment due to agricultural activities, leading to further contamination. Agricultural practices and amendments are the primary sources of soil contamination by micro and nano plastics (MNPs). Especially biosolids, which can transfer MNPs from wastewater to soils. MNPs can release toxic additives and act as carriers for other contaminants. Their effects on soil, microflora, invertebrates, and plants vary, showing positive, negative, or no impact. The interactions of MNPs with other soil pollutants and the diverse sources and behaviors of MNPs in agricultural soils require more research. Key challenges include the lack of standard regulations and stringent guidelines for controlling MNPs in agricultural soils, variability in MNP types and sizes, interference from soil organic matter and minerals, and limitations in analytical techniques. This could be due to unclear classification, lack of awareness about their release, and uncertain health impacts. Given the reliance on plastic products in modern agriculture, it is essential to collect more data on MNP contamination and potential health risks associated with their movement into the food chain. Addressing these research gaps is crucial for developing sustainable management strategies for MNPs to ensure food security. Future research should focus on standardizing methods for MNP analysis, understanding their long-term effects on soil and crops, exploring remediation strategies like phytoremediation, and considering socio-economic and policy implications.

Declaration of interest

The authors declare no conflicts of interest.

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